

AGN OUTFLOWS AND THE MATTER POWER SPECTRUM

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ABSTRACT

We have investigated the effects of AGN outflows on the amplitude of the matter power spectrum in a simple model of spherically symmetric outflows around realistically clustered AGN population. We find that two competing effects influence the matter power spectrum in two opposite directions. First, AGN outflows move baryons from high to low density regions, decreasing the amplitude of the matter power spectrum by up to 20%. Second, high clustering of the AGN transfers the power from small to larger scales. The exact balance between these two effects depends on the details of outflows on small scales, and quantitative estimates will require much more sophisticated modeling than presented here.

Subject headings: cosmological parameters—cosmology: theory—galaxies: active—intergalactic medium—large-scale structure of universe

1. INTRODUCTION

Cosmic shear from weak lensing depends on the matter distribution on all scales, whether the matter is composed of baryons or dark matter. Because it depends on the mass distribution alone, it is also independent of the dynamics of the matter. Weak lensing can offer constraints on the equation of state of dark energy, as it is influenced by the expansion history of the universe. In order to use weak lensing to distinguish between different dark energy models, constraints on cosmological parameters determined from high precision measurements of the matter power spectrum require accurate modeling of the physics on the relevant scales (e.g. Annis et al. 2005). Hagan et al. (2005) have shown the importance of resolving dark matter substructure for simulating the nonlinear power spectrum. Baryons are assumed to closely follow the underlying dark matter distribution on large scales, however, on smaller scales baryons are taking part in more complicated physical processes which can result in a signal comparable to, if not larger than the statistical errors on the matter power spectrum (White 2004; Zhan & Knox 2004; Jing et al. 2006; Rudd et al. 2006). In the recent release of the 3rd year data from the *Wilkinson Microwave Anisotropy Probe* (WMAP) a comparison of cosmic microwave background (CMB) measurements of the amplitude of the matter power spectrum with those of other methods finds weak lensing results to be the most discrepant (Spergel et al. 2006). This discrepancy may simply be a statistical fluctuation, but might also reflect the complicated role the baryons can play in shaping the matter power spectrum at 10% level.

The colossal energy input from active galactic nuclei (AGNs) may also affect the clustering of matter. AGNs are known to influence their environments out to Mpc scales, creating bubbles of hot, tenuous gas around their host galaxies. With kinetic energies corresponding to as little as a percent of their bolometric luminosities, AGNs produce outflows energetic enough to fill large fractions

of the intergalactic medium (IGM) with very low density bubbles (Levine & Gnedin 2005, hereafter LG05). These bubbles effectively push gas aside, influencing the distribution of baryons out to large scales. If AGN outflows are energetic enough to influence the large scale distribution of baryons, it is possible that descriptions of the matter distribution on these scales will need to include them.

In this paper, we investigate the effect of AGN outflows on the matter power spectrum. We continue with the simple model of LG05 and compare the influence of outflows of different kinetic energies on the matter distribution. In Section 2 we describe the outflow model, and our model of the matter distribution and the corresponding power spectrum. In Section 3, we show the effects on the power spectrum for different simulation box sizes, resolutions, and outflow energies. Section 4 is a summary of our findings and their implications.

2. SIMULATION

In the following subsections, we briefly overview a simple model of AGN outflows and the effect they might have on the cosmic density distribution. LG05 describes in greater detail the assumptions behind the outflow model.

2.1. A Simple Outflow Model

Using a particle-mesh code, we simulate an evolving dark matter distribution under the assumption that the gas distribution follows that of the dark matter. We determine the distribution of AGNs within the simulation by introducing a simple constant bias that assumes AGNs will lie in high density regions. By combining a quasar luminosity function constrained by observations (Cristiani et al. 2004; Fan et al. 2001a,b; Schirber & Bullock 2003; Boyle et al. 2000) with some simple arguments about the fraction of AGNs expected to host outflows at any given epoch, we obtain the number of sources to include in the simulation.

We assume that following a brief energy injection from the AGN, spherically symmetric outflows expand according to the Sedov-Taylor blast wave model until reaching pressure equilibrium with their environments. They then remain in pressure equilibrium, and any subsequent expansion (or contraction) is due to the Hubble expan-

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sion and the evolution of the cosmic density distribution within their neighborhoods. The kinetic energy of the outflow is assumed to be a fixed fraction, ε_k of the AGN's bolometric luminosity. Part of this study is to evaluate the role of different kinetic fractions on the large-scale matter distribution.

In the above outflow model, AGNs fill large spherical bubbles with hot, tenuous gas, pushing aside the gas in the IGM in the process. In this model, the intergalactic gas is compressed into thin shells around the outflows. In the calculation of the power spectrum in the next section, we determine the total matter density distribution by including these thin shells of dense matter surrounding the outflows into our model.

2.2. Determining the Matter Power Spectrum

We define the matter density in each cell of the simulation box according to:

$$\begin{aligned} 1 + \delta_m &= \frac{\Omega_{dm}}{\Omega_m}(1 + \delta_{dm}) + \frac{f_b \Omega_b}{\Omega_m}(1 + \delta_{dm}) \\ &= (1 + \delta_{dm}) \frac{(\Omega_{dm} + f_b \Omega_b)}{\Omega_m}, \end{aligned} \quad (1)$$

where f_b is a parameter that determines the local baryon fraction. We assume that $\Omega_{dm} = \Omega_m - \Omega_b$, with 0.27 and 0.04 for Ω_m and Ω_b , respectively. Using the dark matter and outflow distributions, we calculate the total matter density in the entire simulation volume. We assume that cells lying within outflow regions are basically devoid of baryons, and we take $f_b = 0$ in those cells. In cells untouched by outflows, we assume the baryon distribution directly traces that of the dark matter and we take $f_b = 1$. At the outflow boundaries, the weighting parameter is constrained by the average baryon density. We divide the boundary cells into two types: inner and outer boundaries. The weighting parameter for the inner boundary is manually set to lie between 0 and 1, and the weighting parameter for the outer boundary is then determined by the normalization. The results do not appear to have a significant dependence on our choice of f_b at the bubble boundaries. The values adopted for f_b in the present model are an over-simplification, and will provide an upper-limit for the effects of AGN outflows on the matter power spectrum.

We calculate the matter power spectrum for the case in which baryons closely follow the dark matter distribution (without AGN outflows) and for the case in which outflows redistribute baryons. Specifically we are interested in the quantity

$$\Delta P(k)_{AGN} = \frac{P(k)_{AGN}}{P(k)_{nobar}} - 1, \quad (2)$$

where $P(k)_{AGN}$ is the power spectrum including the redistribution of baryons by AGNs and $P(k)_{nobar}$ is the power spectrum determined from dark matter alone (with baryons tracing dark matter on the scales we resolve).

The outflows affect the large scale power via two competing effects in the above model. First, outflows move gas around, redistributing baryons from high to low density regions. This has the effect of decreasing the matter power on a large range of scales. Second, if AGN

outflows only affect the small-scale, immediate environment of host galaxies, high clustering of AGNs transfers the fluctuations from small to large scales. This can be thought of symbolically by representing the gas density as

$$\rho_g(\mathbf{x}) = \hat{L}S[\rho_{g,0}(\mathbf{x})] + \hat{S}S[n_{AGN}(\mathbf{x})], \quad (3)$$

where the gas density $\rho_g(\mathbf{x})$ is represented as the sum of the Large-Scale (LS) redistribution of the “undisturbed” gas density $\rho_{g,0}$ and additional Small-Scale (SS) density fluctuations caused by complex gas dynamical motions around AGNs. The quantities $\hat{L}S$ and $\hat{S}S$ are, in fact, operators in the strict mathematical sense, but if we approximate them as convolutions with some window functions, then the baryonic power spectrum can be symbolically represented as

$$P_g(k) = W_{LS}^2 P_{g,0}(k) + W_{SS}^2 P_{AGN}(k) + \text{Cross Terms}, \quad (4)$$

where the Large-Scale factor W_{LS}^2 is, generally smaller than 1, since one would expect the AGN outflows to move gas from high to low densities, thus reducing the clustering of gas (although, of course, the AGN effect may be very small, in which case W_{LS}^2 could be indistinguishable from unity). The Small-Scale factor W_{SS}^2 is likely to be small, since only a small fraction of all galaxies host AGNs at any given moment, but it is multiplied by a large factor $P_{AGN}(k)$ - the latter is large since AGNs are highly clustered, with bias factors easily as high as 5, depending on redshift and luminosity (e.g. Croom et al. 2005; Lidz et al. 2006). In our model, W_{SS}^2 represents spherically symmetric bubbles, which behave similarly for all AGNs in the simulation. In reality, it should be a much more complex factor, depending on the relevant physics and the AGN environment on smaller scales. The contribution of the second term in Equation 4 also depends on the amount of bias in the AGN distribution. A high bias factor can increase the size of the AGN term significantly. The important point to take is that the AGN term need not be very large (10%) to change the amplitude of the power spectrum by an amount sufficient to bias lensing measurements (1%).

3. RESULTS

In Sections 3.1 and 3.2, we conduct convergence studies of simulation box size and resolution and we study the effects of different energy inputs from the AGNs on the amplitude of the matter power spectrum by varying the kinetic fraction, ε_k .

Figure 7 of Spergel et al. (2006) shows a comparison of CMB predictions for the cosmological parameters Ω_m and σ_8 with the weak lensing predictions from the first analysis of the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) (Hoekstra et al. 2005). We show the following power spectrum results for $z = 0.81$, corresponding to the mean redshift of sources used in the CFHTLS, so that we might comment on their relevance to discrepancies between the two methods.

3.1. Convergence Studies

To test the effects of resolution on the matter power spectrum results, we have calculated the power spectrum for simulation boxes of length $64 h^{-1}$ Mpc with resolutions of 1, 0.5, and $0.25 h^{-1}$ Mpc. Figure 1 shows the resulting $\Delta P(k)_{AGN}$ at two different redshifts. At higher

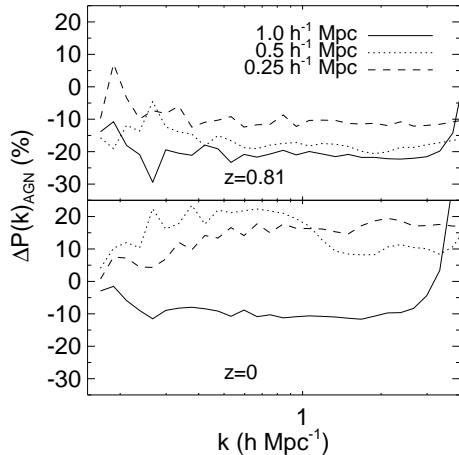


FIG. 1.— Percentage difference between the matter power spectrum with and without the AGN outflow model for simulations of differing resolutions at two different redshifts. Each box is $64h^{-1}$ Mpc across.

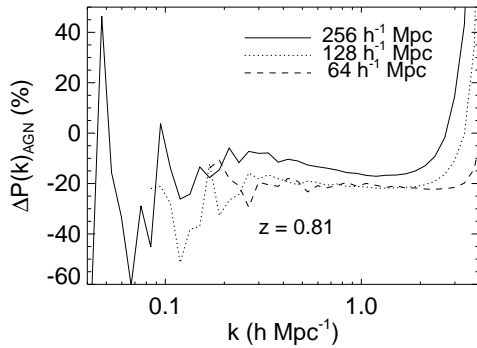


FIG. 2.— Percentage difference between the matter power spectrum with and without the AGN outflow model for different simulation volumes. Each box has cells of length $1h^{-1}$ Mpc.

redshift, the results are somewhat similar for simulations of different resolutions, showing a negative contribution to the amplitude of the matter power spectrum. At $z = 0$, the two higher resolution runs both show positive contributions to the power spectrum. In the high- z case, the AGN outflows move gas around, effectively lowering the amplitude of the power spectrum, while at $z = 0$ it is possible that the effects of AGN clustering dominate, at least for the higher resolution runs.

Figure 2 shows a comparison of the results for boxes of different lengths, but each with the same resolution of $1h^{-1}$ Mpc. The box lengths shown are 64, 128, and $256h^{-1}$ Mpc. The results for each box size are fairly similar, each showing a negative contribution of $\sim 20\%$ to the amplitude of the power spectrum.

Figure 3 shows the redshift evolution of $\Delta P(k)_{\text{AGN}}$ for boxes of length 64 and $128h^{-1}$ Mpc, with $0.5h^{-1}$ Mpc resolution, as well as a $64h^{-1}$ Mpc box with a higher bias factor b . For $z > 1$, $\Delta P(k)_{\text{AGN}}$ decreases as the outflows expand, moving gas onto larger scales. As the filling fraction of AGN outflows levels off at low redshifts, the positive contribution of AGN clustering begins to take over, causing the turnaround in $\Delta P(k)_{\text{AGN}}$ shown for the

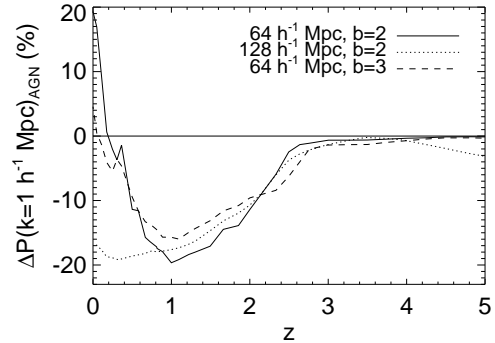


FIG. 3.— Redshift evolution of the percentage difference between the power with and without the AGN outflow model at $k = 1h\text{Mpc}^{-1}$ for $0.5h^{-1}$ Mpc resolution boxes. Two different box sizes and two different bias factors are shown. The turnaround in $\Delta P(k)_{\text{AGN}}$ could be a result of AGN clustering effects dominating over the redistribution of gas by outflows.

smaller volume box. At lower redshifts, the larger volume simulation contains more bright AGNs (larger bubbles) than the smaller volume simulation, so the negative contribution of AGN outflows to the power spectrum continues to dominate. The run with the higher bias factor also demonstrates the positive contribution of AGN clustering to $\Delta P(k)_{\text{AGN}}$, since $\Delta P(k)_{\text{AGN}}$ is greater for $b = 3$ than for $b = 2$.

The convergence studies support our interpretation of the Large-Scale redistribution term in Equation 4, because in the case where the negative contribution of outflows dominates (in the low-resolution simulations; see Figure 2), some convergence takes place. In the resolution study, as demonstrated by Figures 1 and 3, convergence is not as obvious, as we do not model the small-scale fluctuations (the second term in Equation 4) in detail.

3.2. Dependence of the Matter Power Spectrum on Kinetic Fraction

The kinetic energy driving outflows in AGNs is likely linked to the luminosity of the AGNs, but the exact fraction, ε_k is not yet well constrained by observations. As studies of the filling fraction of AGN outflows showed in LG05, the more kinetic energy input from the quasar, the greater the effect on the AGN environments. In this simple outflow model, it only takes a very small fraction of the energy output of AGNs to produce outflows that fill the entire IGM by $z = 2$. In our convergence studies, we have adopted a kinetic fraction of 1%. Here we examine the effects of varying the kinetic fraction on the power spectrum. Figure 4 shows that as little as 1% of an AGN's bolometric energy output produces changes to the power spectrum of up to 20% in the simple model presented here. A kinetic fraction of 2%, or a doubling in the efficiency of the AGN, does not drastically change the effects on the matter power spectrum. The precise dependence of the amplitude of the power spectrum on the kinetic fraction likely depends on the properties of AGNs in a non-trivial way.

4. DISCUSSION AND CONCLUSIONS

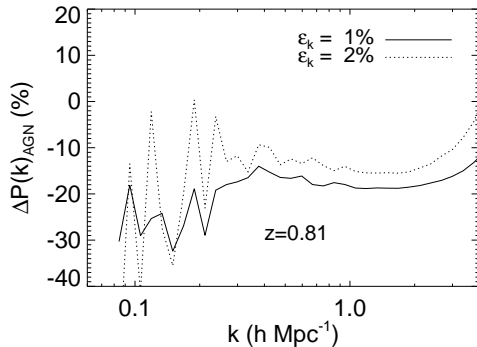


FIG. 4.— Percentage difference between the matter power spectrum with and without the AGN outflow model for models with different kinetic fractions, ϵ_k .

We have found that a simple model in which AGN outflows play a role in the distribution of baryonic matter on cosmic scales results in more than several percent difference in the amplitude of the matter power spectrum. Two competing effects - the removal of gas from high density regions and high clustering of AGNs - make contributions of opposite signs to the matter power.

The amount of energy released in observed AGNs may be sufficient to move all of baryons in the universe over cosmological distances, which would result in the reduction in the matter power spectrum by up to 30%. Observationally, we do not really know whether AGNs do

that or not, but they definitely have the means. It is also possible that the AGN outflows get stopped in the central parts of galaxies, never reaching cosmological scales, or that, even if they reach cosmological scales, outflows expand more quickly into low density regions without affecting higher density regions much.

Additionally, AGNs clustering might influence the power on large scales. Even if AGNs cause non-gravitational fluctuations only on smaller, sub-Mpc scales, these fluctuations propagate to larger, tens of Mpc scales, because the AGNs themselves are clustered more than the baryons as a whole.

Admittedly, our model of spherical outflows is excessively simplistic, and should probably only be considered as an upper limit. Nevertheless, it presents a counterexample to the widespread belief that lensing measurements are insensitive to complex astrophysics.

Unfortunately, the interplay between the two competing effects of AGNs is quite intricate, so even the sign of the total effect of AGN outflows on the matter power spectrum cannot be deduced without further detailed numerical studies of complex gas dynamics on galactic and sub-galactic scales. But the final success of future weak lensing studies of the dark energy will substantially depend on our ability to make a theoretical breakthrough in modeling AGN outflows on a wide range of scales.

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